On the Effects of Projection on Morphology

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ABSTRACT

We study the effects of projection of three-dimensional (3D) data onto the plane of the sky by means of numerical simulations of turbulence in the interstellar medium including the magnetic field, parameterized cooling and diffuse and stellar heating, self-gravity and rotation. We compare the physical-space density and velocity distributions with their representation in position-position-velocity (PPV) space ("channel maps"), noting that the latter can be interpreted in two ways: either as maps of the column density's spatial distribution (at a given line-of-sight (LOS) velocity), or as maps of the spatial distribution of a given value of the LOS velocity (weighted by density). This ambivalence appears related to the fact that the spatial and PPV representations of the data give significantly different views. First, the morphology in the channel maps more closely resembles that of the spatial distribution of the LOS velocity component than that of the density field, as measured by pixel-to-pixel correlations between images. Second, the channel maps contain more small-scale structure than 3D slices of the density and velocity fields, a fact evident both in subjective appearance and in the power spectra of the images. This effect may be due to a pseudo-random sampling (along the LOS) of the gas contributing to the structure in a channel map: the positions sampled along the LOS (chosen by their LOS velocity) may vary significantly from one position in the channel map to the next.

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1. Introduction

In recent years, numerical simulations of magneto-hydrodynamic (MHD) interstellar turbulence in a variety of regimes have been presented by several groups. Some of them have modeled the atomic and ionized ISM at large scales including self-gravity, parameterized heating and cooling and stellar-like forcing from ionization heating (Passot, Vázquez-Semadeni & Pouquet 1995; hereafter Paper I), while others have modeled isothermal flows with random forcing or else in decaying regimes (Gammie & Ostriker 1996; Padoan & Nordlund 1999; Ostriker, Gammie & Stone 1998; Mac Low et al. 1998). The simulations in the latter group may themselves differ in the scale at which the forcing is applied or in the characteristic scales of the random initial conditions of the turbulence. Given the large available parameter space, it becomes necessary to constrain the parameters by comparing the simulation results with suitable observational data. Efforts in this direction have recently started to appear (Padoan, Jones & Nordlund 1997; Heyer & Schloerb 1997; Padoan et al. 1998; Padoan & Nordlund 1999; Heyer & Brunt 1999; Ballesteros-Paredes, Goodman & Vázquez-Semadeni 1999; Rosolowsky et al. 1999; Ossenkopf 1999).

The observations best suited for characterizing the turbulent parameters of the ISM are densely sampled, high-resolution spectral maps of molecular and atomic gas, such as the FCRAO CO Survey of the Outer Galaxy (Heyer et al. 1998) and the Canadian Galactic Plane Survey in HI (English et al. 1998). These provide information on the projected two-dimensional (on the plane of the sky) distribution of the gas, and on the radial component of the velocity. However, because observational data are the result of a complex process which involves integrating the radiation intensity along the line of sight (LOS) through a highly inhomogeneous density field, convolving the result with instrumental noise and response, and then "selecting" the intensity by its frequency to produce a spectrum, it is necessary to investigate the effects of this process and the "distortions" it produces.

In this paper we take a first step towards understanding the "translation" of three-dimensional (3D) physical fields into observational data by investigating the effects of integrating the density of a numerically-simulated field over portions of the LOS where the LOS velocities lie in a certain interval, in order to produce the analogue of spectral-line data from an optically thin medium. Synthetic spectra have previously been produced from simulations by Falgarone et al. (1994), Dubinsky, Narayan & Phillips (1995) and Padoan et al. (1998), in order to compare the synthetic line profiles with actual line spectra. However, in this paper we concentrate on the *morphology* on the projection plane, comparing the spatial distribution of the velocity channels with that of 2D slices of the original 3D density and LOS-velocity fields.

To this end, we use a 3D numerical simulation of compressible turbulence in the ISM,

called ISM128, analogous to the two-dimensional simulations in Paper I, and including self-gravity, parameterized heating and cooling, star formation and rotation. In § 2 we present the equations, parameters and constants of the simulation. In § 3 we present the 3D density and velocity fields in physical (real or configuration) space and discuss some of their physical properties. Next, in § 4 we discuss the position-position-velocity (PPV), or "channel map" representation of the data, noting that important differences arise compared to the physical-space representation. Discussion of the effects of projection is presented in § 5. Finally, § 6 contains the summary and conclusions.

2. The Model

We solve the MHD equations in three dimensions as in the model for the ISM proposed in Paper I. We consider a magnetized self-gravitating single fluid and include model terms for cooling (Λ), diffuse background heating (Γ_d), local heating from stellar activity (Γ_s) and shear. Specifically, we solve the following equations, at a resolution of 128^3 grid points:

$$\frac{\partial \ln \rho}{\partial t} + \nabla \cdot (\ln \rho \mathbf{u}) + (\mathbf{1} - \ln \rho)\nabla \cdot \mathbf{u} = \mu(\nabla^{\mathbf{2}} \ln \rho + (\nabla \ln \rho)^{\mathbf{2}}), \qquad (1)$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{\nabla p}{\rho} - \left(\frac{J}{M}\right)^2 \nabla \varphi - \nu_8 \nabla^8 \mathbf{u} + \nu_2 (\nabla^2 \mathbf{u} + \frac{1}{3} \nabla \nabla \cdot \mathbf{u})$$

$$+ \frac{1}{\rho}(\nabla \times \mathbf{B}) \times \mathbf{B} - 2\Omega \times \mathbf{u} \qquad (2)$$

$$\frac{\partial \ln e}{\partial t} + \mathbf{u} \cdot \nabla \ln e = -(\gamma - 1)\nabla \cdot \mathbf{u} + \frac{\kappa_T}{\rho}(\nabla^2 \ln e + (\nabla \ln e)^2) + \frac{\Gamma_d + \Gamma_s + \rho\Lambda}{e}, \qquad (3)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) - \nu_8 \nabla^8 \mathbf{B} + \eta \nabla^2 \mathbf{B} \qquad (4)$$

$$\nabla^2 \varphi = \rho - 1, \qquad (5)$$

$$P = (\gamma - 1)\rho e, \qquad (6)$$

where ρ is the density, $\mathbf{u}$ the velocity, P the thermal pressure, φ the gravitational potential, Ω the angular velocity due to galactic rotation, $\mathbf{B}$ the magnetic field and e the internal energy per unit mass. In eq. (3) κ_T is the thermal diffusivity and γ the ratio c_p/c_v of specific heats at constant pressure and volume. The temperature T is related to e by $e = c_v T$. Note that the continuity and the internal energy equations are solved in logarithmic variables. The mass diffusion term, in the right-hand side of the continuity equation (1) is added to smooth out density gradients, allowing for greater Mach numbers than otherwise. Momentum and magnetic field dissipation are included by using a hyper-viscosity scheme with a ∇^8 operator, which confines viscous effects to the smallest scales and allows for much

smaller values of the second-order kinetic and magnetic diffusivities ν_2 and η than would be required otherwise (see Paper I).

The non-dimensional parameters which result from the normalization are the Jeans number $J = \lambda_J/L_0 = 0.5$ and the Mach number $M = u_0/c_0 = 1$, where λ_J is the Jeans length and c_0 the adiabatic speed of sound. Although the parameters for run ISM128 are the same as those of the so-called run 28 in Paper I (except for those parameters which are resolution-dependent, such as the viscosities and diffusivities), we have adopted a new set of self-consistent physical units, more appropriate for the 3D case, in which the spatial extention of the simulation box in the vertical direction should not be so large as to bring in serious stratification effects. We have thus re-scaled the units to a box size of 300 pc and a code temperature unit $T_0 = 3000$ K. The chosen values of the J and M parameters then imply a density unit of $n_0 = 3.3$ cm^3, a velocity unit of $u_0 = 6.41$ km s^{-1} and a magnetic field unit of $B_0 = 5\mu$G. In previous papers the domain size was 1 kpc, and the units were $T_0 = 10^4$ K, $n_0 = 1$ cm^3, $u_0 = 11.7$ km s^{-1}, with B_0 unchanged.

The equilibrium temperatures T_{eq} as a function of density are obtained from balancing the heating and cooling functions. For example, at $n = 55$ cm^{-3}, $T_{\mathrm{eq}} = 100$ K, while at $n = 0.1$ cm^{-3}, $T_{\mathrm{eq}} = 9,150$ K. Therefore, the new set of units still provides a reasonably realistic account of the ISM for this range of densities and temperatures.

In this model, the numerical box is centered at the solar Galactocentric distance, with the directions x, y and z taken to correspond to the azimuthal, radial and vertical directions in the Galactic disk, respectively. Note that, although the former coordinates refer to a Cartesian system and the latter to a cylindrical one, no conflict arises, since locally, in the Solar neighborhood, the Galactic coordinates can be approximated by a Cartesian system. All projections are done along the z (vertical) direction, and thus we indistinctly refer to it as "the line of sight" (LOS) direction. Finally, the angular rotation velocity $\mathbf{\Omega}$ is taken equal to that of the Sun, $|\mathbf{\Omega}| = (2 \times 10^8 \text{ yr})^{-1}$.

Details concerning the choice of the model terms for heating and cooling can be found in Paper I. The equations are solved using a pseudo-spectral method with periodic boundary conditions. The temporal scheme is a combination of a third order Runge-Kutta scheme for the non-linear terms, and a Crank-Nicholson for the linear terms. Initial conditions for all variables are Gaussian fluctuations with random phases, with no correlation between the various variables.

3. Real-Space Representation (Density and Velocity fields)

In this section we discuss the density and z-velocity fields in three *spatial* dimensions. For ease of presentation we have chosen to show these 3D data by means of fixed-z planes of the form $(x, y, z = z_0)$, rather than attempting to show the full 3D cubes. We refer to these planes as "slices" through the 3D spatial cubes, perpendicular to the z-axis. Note that these slices correspond to a *single* value of z, contrary to the "channel maps" discussed in the following sections, which correspond to an *interval* of values of the z-velocity u_z.

Figure 1a shows 16 slices through the spatial 3D density cube along the z-direction, with a separation of $\triangle z = 7$ pixels between slices. Whiter (darker) tones denote larger (smaller) values of the field. Figure 1b shows the z-component of the velocity field (u_z) on the same fixed-z planes as in fig. 1a, with black (white) meaning negative (positive) values of u_z.[1]

The spatial structure in run ISM128 exhibits large, interconnected high-density complexes, some of them with abundant expanding shells (left side, central frames in fig. 1a), and some others with not-so-large densities and no star formation (lower parts, bottom frames in fig. 1a). The simulation gives the impression of a large degree of global coherence. Structures along the z-direction can be identified as objects that persist over several frames. For example, the structure seen in the upper-right quadrant is actually a sheet, since it looks elongated (in the up-left to down-right direction), but it also extends from $z = 1$ to $z = 50$. Then from $z = 50$ to $z = 71$, it is seen to contain an expanding shell (another small shell is seen at $z = 8$).

4. Position-Position-Velocity (Channel-Map) Representation

In order to study the effects of projection we have constructed position-position-velocity (PPV) data "cubes" from the 3D density and velocity fields (or cubes). At each position (x, y), the *velocity* axis contains a density-weighted histogram of the z-velocity u_z. "Channel maps" are then constructed as images of the column density with z-velocity between u_z and $u_z + \triangle u_z$ as a function of the remaining two spatial coordinates x and y (the z-direction is integrated out upon computing the column density). In brief, the channel maps are slabs in

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[1] The slices (i.e. constant-z planes) through the u_z cube (which exists in three *spatial* dimensions) should not be confused with the velocity-channel maps discussed in the next section, which are the constant-u_z planes of position-position-velocity (PPV) space. It is an unfortunate coincidence that PPV space is often refered to simply as velocity space, creating a potential source of confusion.

the PPV cube of thickness $\triangle u_z$.

A precise definition can be given as follows. Let μ be the measure defined by $\mu(E; x, y) = \int_E \rho(x, y, z)dz$ where E is a set of points in the LOS at a location (x, y) in the transverse plane. Consider the sets $\{u_z < u\} = \{(x, y, z) \in X \mid u_z(x, y, z) < u\}$, where X is the whole integration domain. The LOS velocity cumulative distribution function ("weighted by density") is defined as $\mu(\{u_z < u\}) = G(x, y, u)$. The density-weighted LOS velocity histogram is thus dG/du. The channel maps, or (x, y) maps of column density associated with points moving with an LOS velocity u_z between u and $u + \Delta u$ are obtained by just taking $(dG/du)\Delta u$. We have the property that the velocity-integrated (over u_z) maps are identical with the maps of the z (spatial) projections of the density field: $\int_{-\infty}^{\infty}(dG/du)du = \int_C \rho(x, y, z)dz$, where C is the whole LOS at (x, y). Figure 2a shows a map of the projected density field (i.e. column density) along the z-direction.

In this paper we employ a relatively low velocity resolution of only 16 velocity channels. However, since here we are not interested in distinguishing velocity features, but rather in investigating the spatial structure seen in the channel maps, such relatively low velocity resolution is inconsequential. On the other hand, excessive velocity resolution would cause poor sampling of the gas along the LOS, due to the low spatial resolution of the simulation. The range of physical velocities is roughly from -6 to $+6$ km s^{-1}, and the channel width is therefore ~ 0.75 km s^{-1}. The 16 channel maps are shown in Fig. 2b.

Note that our choice of using 16 velocity channels and 16 slices through the 3D density and velocity fields is fortuitous, though convenient, since it allows presenting them alongside each other. However, we must emphasize that there is no direct relation between the channel map data and the density or velocity data. While the former refer to fixed $(u_z, u_z + \triangle u_z)$ intervals in PPV space, the density and velocity slices refer to constant-z planes in real (configuration) space. Furthermore, the spatial cubes have a size of $128 \times 128 \times 128$ spatial data points, while the PPV "cubes" (actually parallelepipeds) have a size of 128×128 spatial points $\times 16$ velocity channels.

An important issue to remark is that, due to the method used for their construction, the channel maps may be interpreted in two ways. The standard interpretation is as maps of the spatial distribution of the column density in a given LOS velocity interval. However, they can alternatively be interpreted as *maps of the projected spatial distribution of a given velocity in the LOS* weighted by column density. That is, in the former case one refers to the (projected) spatial distribution of the *density* field, while in the latter one refers to that of the z-velocity field. As we shall see in sec. 5, the latter interpretation appears to be at least as meaningful as the former.

5.   Effects of Projection

5.1.   Morphological similarity between the channel maps and the original velocity field

Comparing fig. 2b to figs. 1a and 1b, we note that the morphology in the channel maps appears more similar to the structure seen in the slices of the spatial u_z cube than in those of the spatial density cube. In order to quantify this effect, we have constructed histograms of the pixel-to-pixel (linear Pearson) correlation function between each velocity channel and each density or velocity slice. That is, for each image pair, we compute the correlation by considering pairs of pixels (one pixel from each image) with the same (x, y) coordinates. This procedure thus estimates the pixel-to-pixel morphological similarity between the two images. Unfortunately, this procedure cannot be used for estimating the similarity between images which do not represent the same object or physical system, since in this case the spatial features in each image are not expected to coincide.

Since the channel maps are LOS integrations while the density and velocity images are slices through 3D spatial cubes, there are no preferred pairs of images between which to compare. We have thus computed the correlation between all possible pairs of images, and then plotted the histograms of the channel map-to-density slice and channel map-to-z-velocity slice correlations. We refer to these as the PPV-ρ and PPV-u_z correlation histograms, shown in figure 3. We see that the histogram of the PPV-u_z correlations contains many more large absolute values than the PPV-ρ histogram. Note that both positive and negative PPV-u_z correlations exist because u_z can be either positive or negative while the PPV-ρ correlations are positive-definite since both the "intensity" in the channel maps and density are also positive definite. This seems to confirm the greater morphological similarity of the z-velocity slices to the channel maps in a statistical sense. We conclude that *the morphology seen in the channel maps is more representative of the projected spatial distribution of u_z than of the column density distribution.* However, it is important to emphasize that the above conclusion does not imply that the channel maps give no information about the projected density distribution, but only that the spatial distribution of the LOS velocity seems to be more important than that of the density in the determination of the structure seen in the channel maps.

What is the origin of the above effect? To see this, consider an incompressible flow. In this case, one can still construct channel maps, in which all the structure is due to the spatial distribution of the velocity field, since the density is a constant. Lazarian & Pogosyan (1999) have independently pointed this out, and numerical experiments to "observe" a non-hydrodynamic, random velocity field with uniform density to produce

channel maps have been performed by Heyer & Brunt (1999). Conversely, consider now an inhomogeneous flow but with constant velocity. In this case, one velocity channel will contain the total projection of the density field. In the general case where neither the density nor the velocity are constants, the structure seen in the channel maps is a complex mixture of the structure in both the density and LOS-velocity fields. The unexpected result found here is that it is the morphology of the LOS velocity field which tends to dominate the channel map structure, at least in the flow regimes we have simulated.

5.2. Small-scale structure

A second result seen from figs. 1a and 2b is that the channel maps contain more small-scale structure than the original spatial density cube, exhibiting sharper structures, edges and filaments, almost as if they had been made at significantly higher resolution.

In order to quantify this, we have computed the power spectra of the two dimensional (2D) density and u_z slices, and of the channel maps (also 2D). The power spectrum is defined in two dimensions as

$$E(k) = \frac{1}{2} \int |\mathbf{a_k}|^2 d\theta_k$$

where $\mathbf{a_k}$ is the Fourier transform of the 2D field, θ_k is the angular coordinate in the Fourier space, and $\mathbf{k}$ is the wave vector with wave number k. The spectra of the density and velocity slices labeled 57 in figs. 1a,b and the spectrum of the channel map labeled 9 in fig. 2b, are shown in fig. 4, with respectively solid, dotted and dashed lines. For clarity we only have shown the spectrum of one representative frame from each cube, but the behaviour we describe is typical of all frames.

Due to the low resolution of the simulation, only marginal power-laws are seen in the spectra of the density and velocity slices. These spectra curve down due to the mass-diffusion and viscous terms in the continuity (1) and momentum (2) equations, respectively. The density-slice spectrum enters this diffusive range at lower wavenumbers because of the lower order of the mass-diffusion term compared to that of the hyperviscous term. The channel map spectrum, on the other hand, is much closer to a power law, and, interestingly, does not curve down at large wavenumbers. This indicates that channel maps "create" their own small-scale structure.

The origin of this larger amount of small-scale power in the channel map spectra might to be due to the fact that density-weighted u_z histograms for nearby points in the projection plane contain in general contributions from points which may be far apart in configuration space. This effect is not noticeable in the total projection because in this case

all points along an LOS are summed over. However, upon differentiation with respect to velocity, the points included in any one LOS are only a small fraction of the total number available, and in general the segments contributing to any given velocity bin may vary significantly from one LOS to the next. This effect may cause the correlation length to be smaller in the channel maps than in the original density or LOS velocity fields. To test for this mechanism, we have performed two experiments: one in which we have replaced the actual LOS velocity field of the simulation by an (x, y)-independent field of the form $u_z(z) = z$, with z in units of the integration box size. The second experiment adds a sinusoidal dependence on the (x, y) position of the LOS, setting $u_z(z) = z + 2\pi\omega x + 2\pi\omega y$, with $\omega = 6$. We find that while the (x, y)-independent case shows a strong drop-off of the channel map spectra (not shown) at small scales, the second experiment restores their larger power content. These experiments confirm that the origin of the small-scale excess power in the channel maps is the (x, y)-dependence of u_z, presumably because it causes the sampling of different sections along z from one LOS to the next. However, the reason why the channel maps do develop power-law spectra, even when the original density and velocity fields do not, remains uncertain to us.

A related effect is that localized structures in the channel maps do not necessarily correspond to localized structures in physical space, and viceversa. For example, the structure labeled A in the 11th velocity channel in fig. 2b is seen to result from the superposition of two density structures also labeled A in slices 29 and 71 of the 3D density field (fig. 1a). Conversely, expanding shells (due to the modeled star formation) are relatively localized in physical space, but extended in PPV space, such as the structure labeled B in slice 64 of the density field (seen since slice 57), which extends from channels 8 through 12 in PPV space. The ambiguity in the correspondence between real structures and structures in PPV space has been previously pointed out by Issa, MacLaren & Wolfendale (1990) and Adler & Roberts (1992).

One final cautionary note is in order. Throughout this paper we have projected and velocity-selected the density field without accounting for any possible thermal broadening, which would spread the contribution of any one fluid parcel in space over various velocity channels, probably smoothing the structure in the channel maps back again (M. Heyer, 1999, private communication).

6. Summary and Discussion

In this work we have presented a 3D simulation of compressible turbulence in an interstellar context (run ISM128). We have discussed the differences between the

representations of the data in physical and position-position-velocity ("PPV" or "channel-map") spaces. Although the heating and cooling functions used in run ISM128 make it non-isothermal, our results are expected to be applicable to cold, nearly isothermal molecular gas observed in optically thin lines as well, since the effects we discussed have a geometrical origin. The main results are as follows:

1. The structure in the channel maps is morphologically closer to the structure in slices through the 3D spatial LOS-velocity (u_z) cube than to that in slices through the 3D density cube. Indeed, the histogram of the pixel-to-pixel correlations between all channel maps and all LOS-velocity slices extends to larger values than the corresponding correlations between the channel maps and the density slices. This implies that channel maps are more representative of the spatial distribution of the LOS velocity than of the density field. Experiments testing the effect of varying the density field on simulated channel maps, using uncorrelated density and velocity fields, have been performed by Brunt & Heyer (1999, private communication), finding that changes in the channel map structure as the imposed density field is varied are relatively minor.

2. The channel maps exhibit more small-scale structure than the density slices, the former having power spectra that curve down systematically (due to the low resolution), while the latter exhibit shallow power laws. The larger amounts of small-scale power in the channel maps may be due to the random superposition of distant structures (in configuration space) with the same velocity along the LOS, because neighboring positions in the projected maps are likely to integrate over different segments of the LOS, producing significant, though artificial, small-scale structure in the channel maps.

3. Another consequence of the previous result is that localization in physical space does not necessarily correspond to localization in channel-map space, and viceversa, an ambiguity already pointed out by Issa et al. (1990) and Adler & Roberts (1992).

The relationship between the density, LOS-velocity and channel map spectra has been investigated theoretically by Lazarian (1995) and Lazarian & Pogosyan (1999). In particular, the latter authors have found that, assuming uncorrelated random density and velocity fields with prescribed spectra, the power spectrum of the channel maps is dominated by the velocity (rather than the density) fluctuations, provided that the density power spectrum is steep enough. This is in qualitative agreement with our result of greater morphological similarity between the u_z slices and the channel maps. However, quantitatively our u_z-slice and channel-map spectra do not look very similar. In fact, at low wavenumbers, the slopes of the channel map spectra (~ -2.2) are very similar to those of the *density* slices rather than to the spectra of the u_z slices, which are sistematically steeper. Furthermore, the artificial small-scale generation in the channel maps does not

seem to be accounted for by Lazarian & Pogosyan (1999), and it should be pointed out that these authors compare the power spectrum of the full 3D fields with that of the intensity maps, while here we compare the channel map spectra to the spectra of the 2D density and LOS-velocity slices. Thus, the two procedures are comparing different quantities in principle. A final difference is that our density and velocity fields, which satisfy the fluid conservation equations, are highly correlated, while Lazarian & Pogosyan (1999) assume uncorrelated fields. Further work is needed to fully understand the differences and similarities between the two approaches.

A final comment is in order. The structural comparisons between channel maps and slices through 3D density and velocity data we have performed in this paper may seem somewhat odd, since it amounts to comparing LOS-integrated data with non-integrated information. However, such is the nature of the complex process of making an observation, and the ability to infer 3D spatial information from its projection in the plane of the sky requires understanding the relationship between the two.

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Fig. 1.— a) Sixteen slices through the 3D spatial density cube of run ISM128 (in logarithmic scale). The separation $\triangle z$ between slices is 7 pixels. The z-coordinate of each plane is given by the number at the bottom of each frame. b) Slices through the 3D LOS-velocity cube through the same planes as in (a) above.

Fig. 2.— a) Total projection of the density field of run ISM128 along the z-direction (i.e., an integrated column density map). Two large complexes with strong events of star formation can be seen on the left hand side of the box. b) The sixteen channel maps of the position-position-velocity $128 \times 128 \times 16$ "cube" (actually, a parallelepiped). The channel velocity width is $\triangle u_z = 0.75$ km s^{-1}.

Fig. 3.— Histograms of the pixel-to-pixel PPV-ρ (solid line) and PPV-u_z (dashed line) correlations for all image pairs. The PPV-u_z histogram clearly contains a larger number of large correlations (in absolute value) than the channel map-$vs.$-density histogram.

Fig. 4.— Power spectra of the 2D images corresponding to the density (*dotted line*) and velocity (*dashed line*) slices labeled 57 in figs. 1a and b, and to the channel map (*solid line*) labeled 9 of fig. 2b. The spectrum of the channel map is seen to contain increasingly more small-scale power with increasing wavenumber than either the density or the LOS-velocity slice spectra.